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LABORATORY EVALUATION OF A SHIPBOARD MULTIFUNCTIONAL WASTE INCI--ETC(U)
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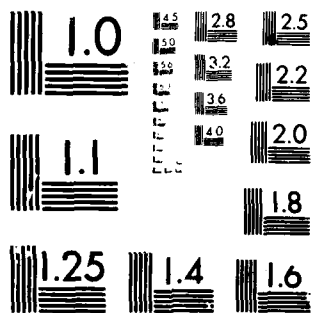
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Block 20. ABSTRACT

and waste oil can be processed on demand at the required flow rates. All wastes can be processed with an average operator attention time of less than 5 min/hr.

Recommendations for certain deficiencies include provisions for extra insulation and safety guards, development of an adequate technical manual, and optimization of feed and fuel processing systems. Upon completion of the recommended modifications, further testing, including a vibration evaluation, will complete the requirements prior to installation of the MFI on board a naval vessel for shipboard evaluations and approval for service use.

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FOREWORD

The work described in this report presents the results of a laboratory evaluation of a shipboard Phase II multifunctional waste incinerator (MFI). The evaluation, initiated 10 March 1978, was conducted in accordance with the test plan formulated by the Naval Ship Engineering Center (NAVSEC), Washington, D. C.

This report was reviewed and approved by J. L. Brumfield, Head, Environmental Science Branch, and D. S. Malyevac, Head, Survivability and Applied Science Division.

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EXECUTIVE SUMMARY

The Navy is currently engaged in a program to develop a multifunctional waste incinerator (MFI) as an alternative to the overboard discharge of potentially harmful wastes from its seagoing vessels. The laboratory evaluation of a Phase II MFI consisted of testing the unit for a minimum of 1200 operational hr to characterize performance, reliability, maintainability, habitability, and safety. This evaluation, initiated 10 March 1978, was conducted in accordance with the test plan formulated by the Naval Ship Engineering Center, Washington, D.C.

Upon completion of the laboratory evaluation, the MFI demonstrated that the solid waste processing requirements are acceptable for various wastes with a 98-percent average reduction efficiency on a weight basis. Additionally, freshwater sewage and waste oil can be processed on demand at the required flow rates. All wastes were processed with an average operator attention time of 3.4 min/hr, which is well below the 5 min/hr requirement.

Critical failure and corrective maintenance requirements were exceeded; however, most of the failure and maintenance events that occurred could have been prevented if adequate maintenance sections were available in the technical manuals.

Requirements were met for flue gas temperature maximums and noise criteria. Refractory deterioration was determined to be repairable with suitable patch material.

Recommendations for certain deficiencies include provisions for extra insulation and safety guards, development of an adequate technical manual, and optimization of feed and fuel processing systems. Upon completion of the recommended modifications, further testing, including a vibration evaluation, will complete the requirements. This testing will be performed prior to installation of the MFI on board a naval vessel for shipboard evaluations and approval for service use.

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INTRODUCTION

An ever-increasing concern for the environment has produced a common awareness for environmental protection. Previous executive directives^{1,2} resulted in the Federal Government's taking the lead in developing control devices to prevent pollution. The Navy is currently engaged in a program to develop a multifunctional waste incinerator (MFI) as an alternative to the overboard discharge of potentially harmful wastes from its seagoing vessels. The total program encompasses the basic research and development of a central processor capable of handling shipboard-generated trash, food waste, concentrated oil waste, and sewage sludge from a sewage treatment system. The program consists of three phases:

Phase I--Development of a full-scale prototype unit

Phase II--Laboratory evaluation of a land-based system

Phase III--TECHEVAL/OPEVAL testing of the optimum system on board a Navy ship

Phase I testing was completed at the Naval Surface Weapons Center (NSWC) Dahlgren, Virginia, in June 1976.³ The results of Phase I testing were used to upgrade the system for the Phase II design. The Phase II evaluation consisted of testing the unit for a minimum of 1200 operational hr to characterize performance, reliability, maintainability, habitability, and safety. This evaluation, initiated 10 March 1978, was conducted in accordance with the test plan formulated by the Naval Ship Engineering Center (NAVSEC), Washington, D.C.⁴

OBJECTIVE

The objective of the MFI Phase II (MFI-II) evaluation was to collect data pertinent to the quantification and qualification of performance, reliability, maintainability, habitability, and safety characteristics of the multifunctional waste incinerator. Results will be used to determine if the prototype unit meets established requirements for a shipboard incinerator.

DESIGN REQUIREMENTS

The general design requirements for the MFI-II were that it:

1. Continuously or intermittently process solid wastes (115 lb/hr minimum trash and refuse with and without 20-percent plastic, 66 lb/hr garbage, 55 lb/hr dense trash, and 70 lb/hr (max) boxes) and freshwater

and saltwater sewage, while firing the main burner with No. 2 fuel oil, JP-5 aviation fuel, or waste oil, on demand and with smokeless operation

2. Produce residue for solid waste containing no more than 2-percent organic matter by weight, as determined by weight loss on heating procedures
3. Require operator attention time less than 5 min/hr
4. Conform with reliability/maintainability requirements as follows:
 - a. 500 operating hr mean time between failures (MTBF)
 - b. 300 operating hr mean time between corrective maintenance (MTBCM)
 - c. 95 percent of maintenance events to be completed in less than 5 hr
5. Require minimum manual stoking and ash removal
6. Contain materials best suited to resist corrosion from processing requirements
7. Conform with design stack gas emission criteria
8. Maintain stack gas temperatures at less than 650°F
9. Operate without producing offensive odors
10. Operate in a safe manner without producing hazards to operating and maintenance personnel
11. Conform with the Category D minus 10-dB requirement of MIL-STD-740B⁵ (SHIPS) for noise criteria of shipboard equipment in machinery spaces
12. Maintain surface temperatures at less than 140°F
13. Be provided with an adequate technical manual with instruction on operation and preventative maintenance
14. Conform with criteria of MIL-STD-167-1⁶ for shipboard vibration

Figure 1 depicts the basic construction features of the MFI-II unit. Solid waste is ram-fed from the feed hopper into the main chamber. Combustion gases pass through the main chamber, upward into the sewage chamber, and through the cooling chamber prior to entering the fly ash collector and exiting to the stack. The master control panel is separate from the incinerator module and provides control of all process functions. The operator control panel controls all automatic feeding operations.

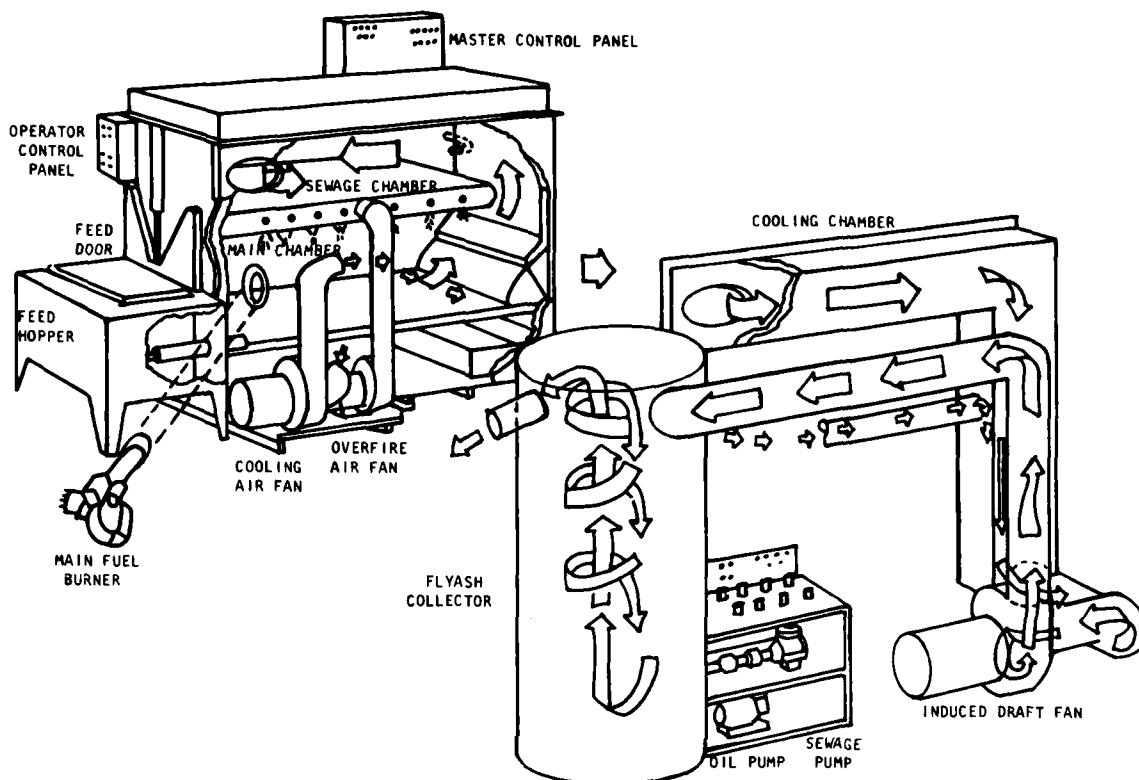


Figure 1. Artist's Sketch of MFI Phase II

TEST RESULTS

PERFORMANCE

Figure 2 shows the MFI-II being fed during the laboratory evaluation. The MFI-II was evaluated in accordance with the formal MFI test plan on the capability to process and to burn at specified rates solid wastes, sewage, and waste oil. Additionally, the completeness of burn and operator attention time were considered in the performance evaluation. Burn rates were prescribed by the test plan and were followed throughout the testing. Solid wastes were tested in the seven categories listed in Table 1, and the values given are the average rates during the actual test.

The main fuel used in the first 75 tests was No. 2 fuel oil, while JP-5 (jet engine fuel) was used in the last 75 tests. No sewage was burned during

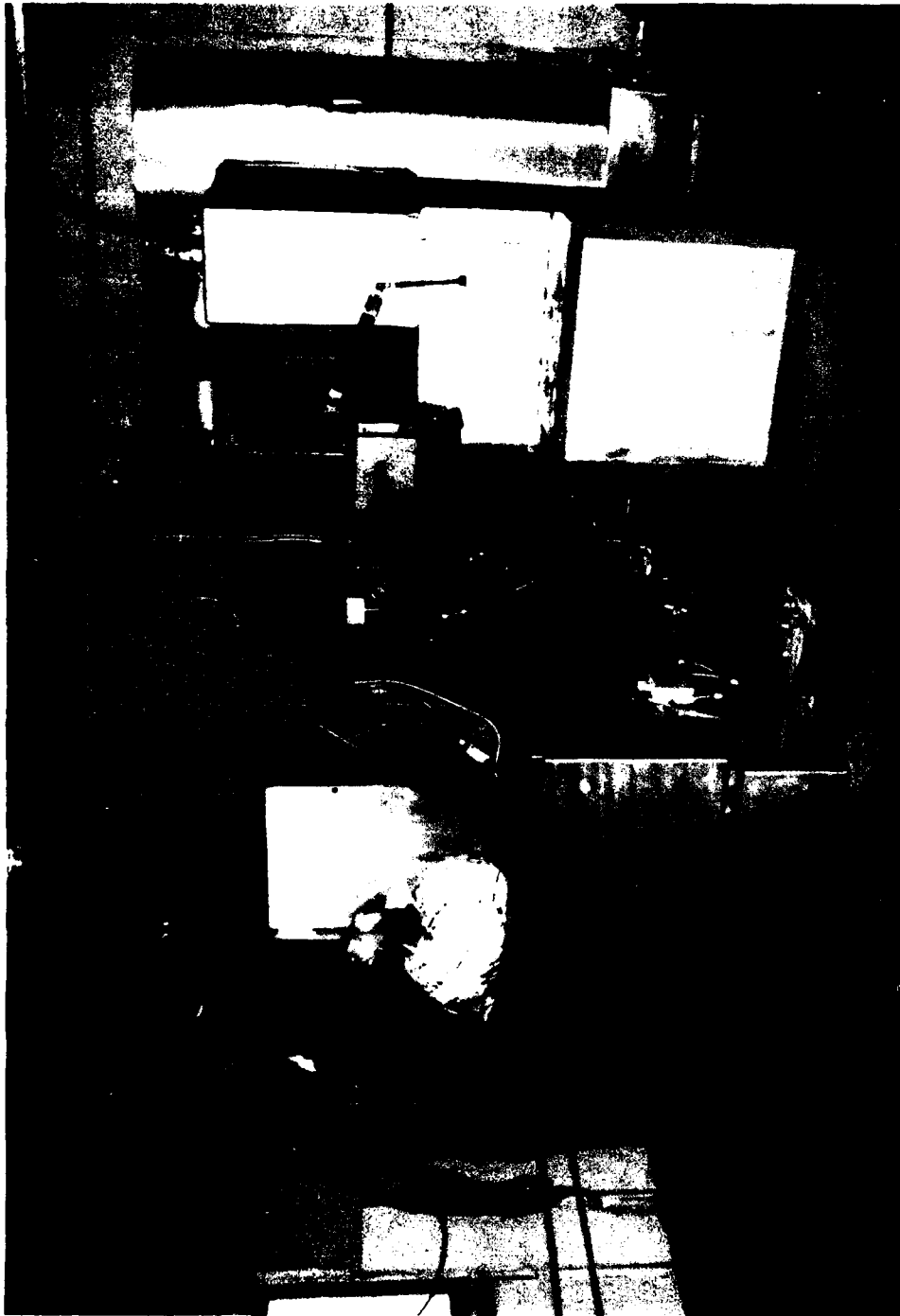


Figure 2. Multifunctional Waste Incinerator During Laboratory Evaluation

the first 50 tests. Both saltwater and freshwater sewage (primarily freshwater sewage) were burned during the last 100 tests. A total of 1257 operational hr was accumulated during the laboratory evaluation.

Table 1. Burn Rates for the MFI-II Tests

Material	Burn Rate (lb/hr)	No. of Feeds per 7-hr Test
Refuse	120	7
Trash	115	6
Garbage	66	2
Dense trash	55	2
Trash with 20-percent plastic	115	2
Refuse with 20-percent plastic	120	2
Boxes	70	2

Ash data were collected every fifth test. No ash data are available for certain wastes such as dense trash because of the arrangement and sampling procedure of the test plan. Ash sampling and analysis were performed in accordance with an Environmental Protection Agency (EPA) procedure⁷ set forth in the test plan. Consumption and combustion performance data for three categories of solid waste are summarized in Table 2. Percentage values are averages calculated from individual test values. The solid waste reduction calculations* are:

$$\text{Percent Reduction Efficiency} = \left(1 - \frac{(\text{Ash Wt} - \text{Unburned Wt}) (\% \text{ WLOH})}{(\text{Total Feed Wt} - \text{Unburned Wt})} \right) \times 100$$

$$\text{Percent Material Remaining} = \frac{\text{Total Ash Wt}}{\text{Total Feed Wt}} \times 100 \quad \text{Percent Remaining w/o Unburned} = \frac{\text{Ash Only Wt}}{\text{Total Feed Wt}} \times 100$$

Fuel and sewage consumption rates are averages of those rates used in each test involving the particular material listed in the first column for which ash data were taken.

As can be seen from Table 2, the weight loss on heating (WLOH) in the ash is much greater in all categories than the 2-percent value imposed by the test plan. During the last 15 tests, manual stoking was increased on selected tests to see if WLOH could be decreased. Table 3 presents the results obtained, which show that no trend exists between stoking and WLOH. Values less than 2-percent could not be obtained by varying the degree of manual stoking. Analyses were performed on ashes that accumulated in the sewage chamber and in the fly ash collector hopper. Values obtained were 3.1 percent for sewage ash and 11.0 percent for the fly ash. The average WLOH for all materials in Table 2 is 21.1 percent. The report⁷ for the EPA procedure was consulted and values were compared with the report values for municipal incinerators. Reported

* Do not use values in Table 2.

Table 2. Average Material Consumption and Combustion Performance During MFI-II Tests

Material Burned	Main Fuel Waste (lb/hr)	Sewage Burned (lb/hr)	Weight Loss on Heating (%)	Reduction Efficiency (%)	Remaining Total (%)	Remaining w/o Unburned Material (%)
Refuse	33.9	--	33.2	96.5	10.2	4.8
Refuse	--	28.2	23.8	97.0	15.2	12.3
Refuse	52.3	--	41.8	96.7	16.0	7.1
Refuse	--	38.6	33.9	97.3	14.3	7.0
Trash	26.4	--	7.3	99.3	15.7	9.2
Trash	--	17.4	23.0	97.4	17.1	10.9
Trash	38.8	--	9.0	99.1	17.4	8.6
Trash	--	32.8	11.3	99.0	17.5	8.2
GTR*	31.7	--	NA**	NA	14.0	NA
GTR	--	34.5	6.3	99.7	8.6	5.1
GTR	49.6	--	20.7	98.5	17.1	6.8
GTR	--	39.1	22.0	98.7	11.1	4.8

* GTR -- Garbage/Trash/Refuse

** Not available as per criteria of test plan.

average values for WLOH were 21.4 percent for fine incinerator residue (refuse fired) and 3.5 percent for fly ash from the same incinerator. This comparison shows that the MFI-II performs in the same manner as a municipal incinerator.

Table 3. Effect of Increased Stoking on WLOH

Trash			Refuse		
Stokes			Stokes		
Test	Per Hr	% WLOH	Test	Per Hr	% WLOH
135	0	5.4	-	-	-
137	1	2.6	130	1	43.4
138	1	7.5	140	2	24.7
139	2	3.2	141	2	50.8
142	3	8.2	150	3	42.3
145	3	8.5	-	-	-

The experimental averages for WLOH and the percent reduction efficiency from Table 2 were plotted to give the correlation shown in Figure 3. From this relation, a value less than 2-percent WLOH would require an efficiency of 99.9 percent or better. The average efficiency for the MFI-II during the 1200-hr test was 98.1 percent. An increase in firebox temperature was considered as a solution to reducing the WLOH; however, during sewage tests, the firebox temperatures reached as high as 1950°F (550°F above the firebox set point) without producing the required WLOH. Based on the above considerations, the 2-percent WLOH criterion appears to be too stringent for the state-of-the-art design.

The operator attention time for the MFI-II is required not to exceed 5 min/hr. The average value for the entire 1200-hr test period was 3.4 min/hr, and the distribution for the operator attention time is shown in Figure 4. The requirement was exceeded 6 percent of the total test hours, primarily in the 4th and 5th hr of operation, during the first 37 tests and the last 10 tests. The excessive attention time was initially due to buildup of ashes and solid wastes (refuse or trash) in the firebox because of an improper setting on the ash door timer. The problem was alleviated by resetting the ash door timer, as per NAVSEC request, to allow the ash door to open on each full forward stroke of the ram. This action allowed ashes to be pushed from the firebox during each feed cycle, thereby reducing buildup. Operator attention time during the last 10 tests was increased because of increase in stoking as required to conduct the tests discussed earlier pertaining to the WLOH. Operator attention time was exceeded by only 1 percent during tests 38 through 140. Attention time during these tests was due to a series of isolated problems, such as initial debris behind the ram, one fire in the hopper that was cleared with a rake, and binding of the ram due to feed hopper warpage. Additionally, operator attention time during feeding is affected by low-density loose trash, which requires more feeds to process the required hourly weight of materials; however, this does not increase attention time beyond the 5-min/hr specification.

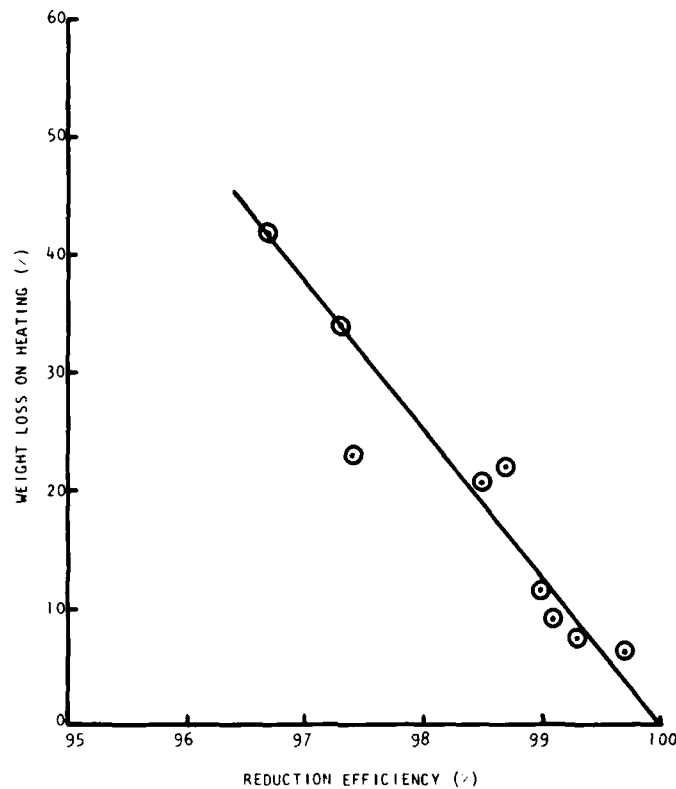


Figure 3. WLOH of MFI-II Ash vs Reduction Efficiency

Numerous actions other than feeding comprise the operator attention time. These include ram jams, door jams, stoking, fires in the feed hopper, debris in feed hopper requiring cleaning, minor maintenance, flameouts requiring manual reset, ram malfunctions, and cleaning of hopper door. Maximum values for actions affecting operation are presented in Table 4 with the test in which they occurred. Some events also affect maintainability, which is discussed in the next section.

RELIABILITY AND MAINTAINABILITY (R&M)

The requirement for R&M must be adequately determined to ensure that the incinerator will perform its intended mission in an acceptable manner. A discussion of the factors involved in the quantitative analysis will be presented here on a point-to-point basis to further detail situations encountered during the laboratory evaluation.

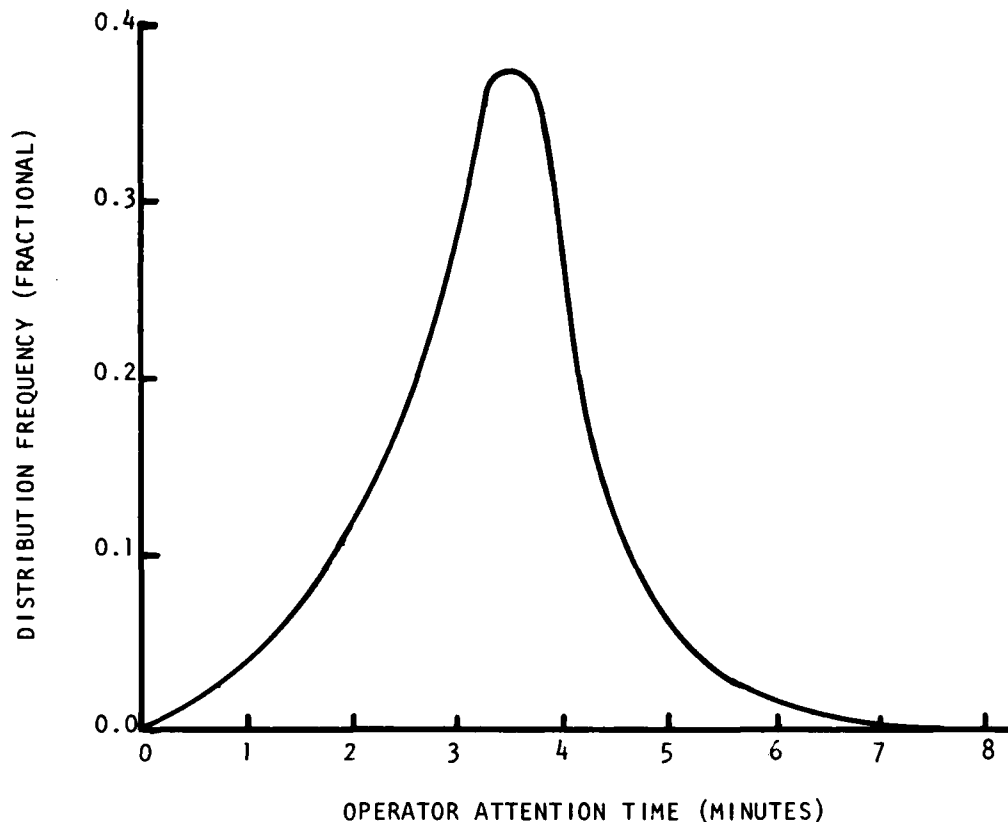


Figure 4. Distribution of Operator Attention Time

Failures

Critical failures were attributed to the following: (1) scaling in the metering pump on the fuel-oil burner, (2) deterioration of piston seals in the feed door pneumatic cylinder, (3) bearing failure in the fuel-oil burner motor, and (4) an integrated circuit failure in the firebox temperature controller. Detailed diagnostic reports are given in the appendix. Material buildup in the fuel-oil system occurred from the processing of waste oil containing fine dust. The fuel delivery system used during the test program, which is external to the MFI, contained only strainers prior to the burner process components. The use of finer filters instead of strainers would have eliminated the scaling from material buildup and consequent failure of the metering pump. Piston seals failed after 1200 hr of actual operation, and failure appeared to be attributed to temperature embrittlement from their proximity to high-temperature regions above the feed door. The original Neoprene seals were replaced with fluorocarbon elastomer seals, which will better endure this environment. The bearing failure occurred after 960 hr of operation. Disassembly of the motor showed double-sealed bearings. Failure

Table 4. Events Affecting MFI-II Operation

Event	Maximum Per Test	Minimum Per Test	Average Over 150 Tests	Standard Deviation Over 150 Tests
Ram jam	11 (10)*	0 (150)	0.41	1.33
Door jam	5 (148)	0 (150)	0.45	0.91
Door jam auto clear	21 (19)	0 (150)	1.23	2.83
Door jam manual clear	9 (19)	0 (150)	0.59	1.24
Stoke	23 (145)	0 (135)	9.73	3.54
Fire in hopper	12 (19)	0 (150)	0.29	1.20
Debris in hopper	1 (91)	0 (150)	0.01	0.12
Flameout	4 (114)	0 (150)	0.27	0.70
Shutdown for maintenance	1 (143)	0 (150)	0.02	0.14
Shutdown for power failure	2 (5)	0 (150)	0.03	0.20
Ram malfunction	1 (12)	0 (150)	0.01	0.12
Clean hopper door	2 (19)	0 (150)	0.02	0.18
Door malfunction	0 (150)	0 (150)	0.00	0.00
Ash door malfunction	1 (28)	0 (150)	0.01	0.12

* Test numbers in parentheses

appeared attributable to loss or lack of lubrication. Failure could have been prevented by ensuring adequately high-temperature grease was used for lubrication. Additionally, failure rate can be extended through specification of precision tolerances on bearing construction. The failure of the integrated circuit within the temperature controller appeared to occur from defective construction of the chip circuitry. Figure 5 shows the damage to the chip circuitry at failure. Also, copious debris was observed upon decapsulation of the integrated circuit. This material was present as a result of the fabrication process and could have been prevented by proper quality control by the manufacturer. It is quite possible that this debris aligned itself between two potentials and formed a bridge for an electrical short circuit. This type of malfunction is considered a true failure of the device and can be accommodated most easily by replacement with a spare temperature controller.

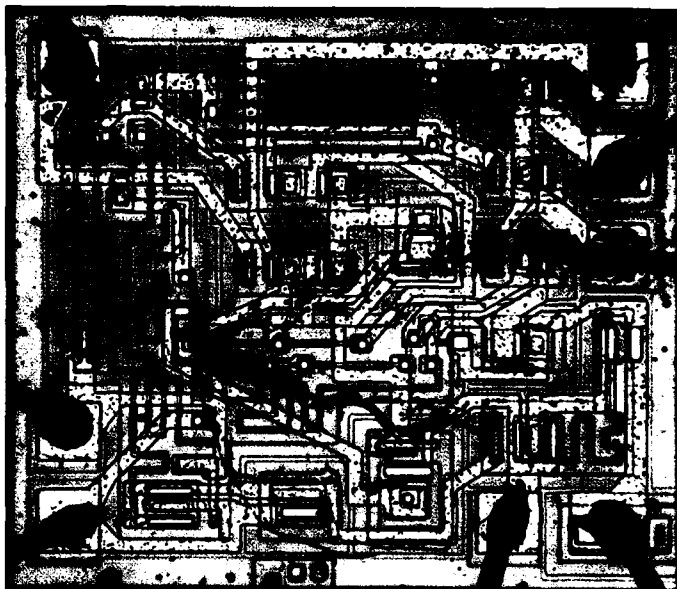


Figure 5. Integrated Circuit Failure on MFI-II Temperature Controller

Based on the singular failure of the temperature controller, a projected reliability can be calculated as follows:⁸

$$\text{Reliability} = \frac{\text{Number of Successful Missions}}{\text{Number of Total Missions}}$$

$$= 149/150$$

$$= 0.993$$

Using an exponential failure estimate for an 8-hr daily operation, the projected MTBF is calculated as follows:

$$R = \exp (-t/\theta)$$

$$0.993 = \exp (-8 \text{ hr}/\theta)$$

$$\theta = 1196 \text{ hr}$$

where

R = Reliability
t = Time for daily mission (hr)
 θ = Mean time between events (hr)

Maintenance

Corrective maintenance during the formal test program included primarily those events not covered in the technical manual as preventative maintenance; e.g., cleaning the fuel-burner nozzle, repairing limit switches, replacing fuses, cleaning the sewage nozzle, and refurbishing fuel-burner components.

Two of the criteria for R&M were that the distribution of corrective maintenance repair times be such that 95 percent of the maintenance events can be completed in less than 5 hr and that MTCBM be 300 hr minimum. A total of 20 corrective maintenance events occurred during the laboratory evaluation. The quantification of the maximum maintenance time characteristics was based on the assumption that repair times are distributed lognormally and that the maximum corrective downtime (DT) is described by the following equation:⁸

$$\log DT = \bar{D}_{cm} + 2.2 s_{cm}$$

where

DT = Maximum corrective downtime

\bar{D}_{cm} = mean of the logs of the corrective maintenance downtimes

2.2 = factor for one-sided tolerance limit for normal distribution for 0.95 probability at 0.90 confidence for 20 maintenance events

s_{cm} = Standard deviation of the logs of the corrective maintenance downtimes.

Table 5 summarizes the corrective maintenance data obtained during the laboratory evaluation. Using the log DT data and substituting into the previous equation yields

$$\log T = \bar{D}_{cm} + 2.2 s_{cm}$$

$$\log T = -0.47 + (2.2) (0.50)$$

$$T = 4.2 \text{ hr}$$

which is less than the 5-hr requirement.

Table 5. Corrective Maintenance Events

Event	Test	Maintenance Item	Operating Time (hr)	Downtime DT (hr)	log DT
1	5	Feeder	38.69	1.20	+0.08
2	12	Feeder	94.22	0.05	-1.30
3	18	Burner	143.19	0.08	-1.08
4	30	Feed door	243.62	0.05	-1.30
5	40	Burner	330.84	0.33	-1.48
6	48	Feeder	402.67	0.30	-0.52
7	63	Feed door	522.77	0.33	-0.48
8	75	Burner	630.22	0.83	-0.08
9	76	Sewage relay	632.82	2.17	+0.34
10	108	Feed door	903.69	0.17	-0.77
11	108	Salt cake	903.69	2.50	+0.40
12	126	Feeder	1048.89	0.17	-0.77
13	128	Feeder	1065.04	0.42	-0.38
14	131	Feeder	1092.14	0.17	-0.77
15	132	Draft damper	1092.14	0.17	-0.77
16	134	Burner	1117.37	2.00	+0.30
17	135	Burner	1120.47	0.47	-0.33
18	143	Burner	1188.05	0.67	-0.17
19	146	Feeder	1222.65	0.17	-0.77
20	148	Feeder	1231.65	0.25	-0.60

$$\bar{D}_{cm} = -0.47$$

$$S_{cm} = 0.50$$

Unscheduled maintenance was limited primarily to that required to the fuel-oil burner and various limit switches on the ram-feeder system. Proper scheduling of preventative maintenance checks on the burner items, such as refilling reservoirs, cleaning the drawer assembly, and performing the proper adjustments on a monthly basis, could have eliminated approximately 30 percent of the burner maintenance. Loose limit-switch arms were encountered on both the ram feeder and the feed door. This maintenance item was eliminated by firmly securing the actuator arm in place, using adhesive compound on the set screws. Additional maintenance was required with the feeder system when warpage of the feed hopper bottom and side walls occurred, due primarily to prolonged exposure to high firebox temperatures and to minor fires occurring intermittently within the hopper. This produced interference between the hopper wall and the feed door, resulting in ram jams. Correction of this maintenance item is discussed in the next section.

Other maintenance actions consisted of cleaning dust from the sewage pump relay, tightening a loose set screw on the damper shaft, and cleanout of the saltwater sewage cake. During testing, the electrical enclosure was more susceptible to a dusty environment because of ash analyses and test instrumentation setup requiring penetration of the original enclosure. These

conditions are more severe than those found on board ships. Loose set screws can be prevented by proper fastening techniques.

The burning of saltwater sewage presented the most critical unscheduled maintenance action. After eight tests with saltwater sewage (4.6-percent solids average), considerable ash cake developed in the sewage chamber, as shown in Figure 6. Table 6 gives the qualitative analyses of this ash cake. Cleanup of the sewage chamber required hammering and chiseling of the ash cake to the depth of the refractory-cake interface. Consistency of the ash cake was very solid, making it difficult to discern where ash cake stopped and refractory began. After several attempts to remove the cake in layers, the decision was made to remove only the bulk of the ash and leave approximately a 2 in. depth of cake remaining on the sewage compartment floor. The cleaned chamber is shown in Figure 7. Removal of the sewage ash cake from the plastic refractory wall (center right of Figure 7) was much easier and cleaner than on the castable floor area. The buildup and adhesion of the saltwater sewage cake may be eliminated by a combination of system modifications, such as lowering chamber temperature, optimizing nozzle characteristics, and changing materials of construction throughout the sewage chamber (such as use of phosphate-bonded, alumina-chromic oxide plastic refractory).

Table 6. Qualitative Analyses of Samples

Sample	Test 62 (5142*)	Test 83 (5143)	Test 118A (5144)	Test 118B (5145)
Silicon	L**	L	L	M
Iron	Tr	Tr	L	L
Manganese	Tr	Tr	Tr	L
Lead	M	M	L	M
Tin	M	M	L	M
Chromium	Tr	Tr	ND	Tr
Magnesium	L	L	L	L
Aluminum	M	M	M	D
Molybdenum	L	L	Tr	L
Vanadium	ND	ND	Tr	Tr
Bismuth	Tr	Tr	Tr	Tr
Copper	M	M	L	M
Silver	M	M	M	M
Zinc	L	L	Tr	L
Sodium	D	D	VD	VD
Titanium	Tr	L	Tr	L
Potassium	L	Tr	ND	Tr

* Lab file number

** VD--Very heavy concentration

D--Heavy concentration

M--Medium concentration

L--Light concentration

Tr--Trace

ND--None detected



Figure 6. Ash buildup in Sewage Chamber After Saltwater Sewage Tests



Figure 7. Cleanout of Sewage Chamber After Saltwater Sewage Tests

Assuming an adequate preventative maintenance schedule had been available during testing, the unscheduled corrective maintenance event pertinent to the MFI-II system during the laboratory evaluation was the sewage chamber cleanout. Using a one-sided confidence interval, the projected MTBCM can be estimated using the following equation:

$$\text{MTBCM (90-percent confidence)} = \frac{2T}{\chi^2 (0.10, \gamma)}$$

where

T = Total number of operational hr

$\gamma = 2(\text{CM} + 1)$ and CM are the total number of corrective maintenance items

$\chi^2 (0.1, \gamma)$ = Chi square value at the 90-percent confidence level and γ degrees of freedom

Substituting in the appropriate values into the equation above gives

$$\text{MTBCM} = \frac{2 (1256.84 \text{ hr})}{7.78}$$

$$\text{MTBCM} = 323 \text{ hr}$$

which conforms to the test plan requirement.

Coupled with the maintenance items discussed above are the scheduled maintenance events performed on a daily, weekly, monthly, and quarterly basis. The most significant maintenance item is the cleanout of the sewage chamber. This requires a person climbing into the firebox, standing in the entrance of the sewage chamber, and raking or chipping sewage ash cake from the sewage chamber floor. Such actions are unacceptable since they require personnel to work in a confined, dusty environment, wearing protective clothing and dust masks. Provisions for cleanout from an external position are now being investigated and will be incorporated in the existing incinerator.

Inherent in the maintenance performed is the adequacy of the existing technical manual.⁹ Typically, the manual was found to be inadequate regarding detailed explanation of procedures for adjustment of items such as limit switches, recommended tools and maintenance procedures, and detailed drawings necessary for troubleshooting and repair (see Table 7 for specific examples). Also, although the organization follows military standards, it makes certain procedures difficult to follow. For example, several major sections may have to be consulted before precise procedures for performing maintenance on the fuel-oil burner are finally located. During the formal test program, it was concluded that certain corrective maintenance actions should actually have been included in the technical manual as preventative maintenance actions if corrective maintenance data were available when the manual was written. A supplemental section to the incinerator technical manual, including the manufacturers' technical information regarding ancillary equipment, such as the burner or the fans, would be a major benefit.

Table 7. Technical Manual Deficiencies

Item	Technical Manual Deficiency
Ram feeder limit switch LS-5 problem	No detailed explanation given as to location, angle, position, tools required, or procedure for adjustment
Cleanout of fly ash collector required weekly	Manual shows monthly cleanout
Bottom of feed door covered with melted plastic	Manual does not give recommended cleaning tools/procedures.
Sewage nozzle replacement	Assembly drawing is required.
Main burner	Burner pressure adjustment should be listed in order required with detailed instructions on what is to be adjusted, how to adjust it, and where it is found. Discussion of burner parts is scattered throughout the manual, and it should be located in one thorough section. Preventative maintenance schedule is inadequate.
Troubleshooting diagrams refer to SV-6, RBR, GS-2 or Para. 3.	These items should be defined (i.e., limit switch, LS-2, ram feeder, electrical dwg 2, Page 61) on or near the drawing.
Ram feeder, air manifold, pneumatic pistons, and all fans	These require detailed assembly drawings and instructions.

Auxiliary Equipment

Certain problems with equipment necessary for the operation of the MFI-II, but not considered part of the system during the evaluation, are discussed here to be documented while encountered throughout the testing. As mentioned under Failures, problems were encountered with the fuel-oil system because of inadequate in-line filters/strainers. After approximately 380 hr of operation, the circulating oil pump showed indication of reduced output pressures. Disassembly showed damage (0.001- to 0.002-in. grooves) to the impeller and internal wear of the pump body (Figure 8). Replacement was made with a new pump; however, approximately 308 hr later the new pump failed and required replacement. The pump manufacturer was consulted, and the original belt drive operation was replaced by direct drive operation. Fine felt filters were installed upstream of the pump to ensure proper filtration of No. 2 fuel oil. No further wear on the pump was experienced after making these modifications.

After approximately 540 hr of operation, sewage flow rates were observed to decrease by 30 percent. Disassembly of the sewage delivery pump showed wear to the stator and rotor (Figures 9 and 10). Failure occurred after the 10 tests (82 hr) with saltwater sewage. Replacement was made with a new pump, and no further problems occurred after returning to freshwater sewage.

FEED SYSTEM

The feed system interlocks to prevent overfeeding consist primarily of a timer and counter. These components control solid waste feed by allowing only a predetermined number of feeds over a specified time frame per hour of waste processed. Early in the test program, it was discovered that the feed system logic could be circumvented when material became lodged under the guillotine door. The operator could perform another feed cycle before a time-delay circuit energized a warning light. Additionally, the current feed count would be maintained. Another inconvenience to the operator was the loss of feed counts due to the time lag in the feed push-button circuit. If the push-button is not held in the energized position for approximately 3 sec, the feeder does not cycle, and a count is lost. Changes in the percent interlock wiring and optimization of feeder controls should alleviate future occurrences of overfeeding.

Maintenance of the feed system consisted primarily of tightening loose limit switch arms and cleaning the buildup of debris from behind the ram face. Figure 11 shows the buildup that occurs over an interval of 20 tests. Such transfer of material can be prevented by securing the hopper lid and enclosing the opening formed on a ram forward cycle.

Near completion of the laboratory evaluation, warpage of the feed hopper bottom and side walls was observed (Figure 12). This was attributed primarily to prolonged exposure of the hopper to the high firebox temperature and to minor fires occurring periodically within the hopper, typically during feed door malfunctions. The ram feeder bottom was disassembled, and its fabrication was found to be inconsistent with the design drawings. Inadequate welds failed when exposed to high temperatures, allowing the 10-gage stainless steel liner to deform. The liner was replaced with 3/16-in. stainless steel plate, and adequate welds were made to original and additional structural members. Side panels of the hopper were squared simultaneously with other repairs.

During disassembly of the feeder unit, several fasteners were found to be missing or loosened. Upon reassembly, lock washers were installed to prevent future problems with fasteners vibrating loose.

STOKING TESTS

Although some stoking is afforded by the underfire air, buildup of metal and other unburned material necessitated manual stoking during the evaluation period. Test personnel became aware of explosion hazards when the burning trash contained pressurized containers such as aerosol cans. Figure 13 shows

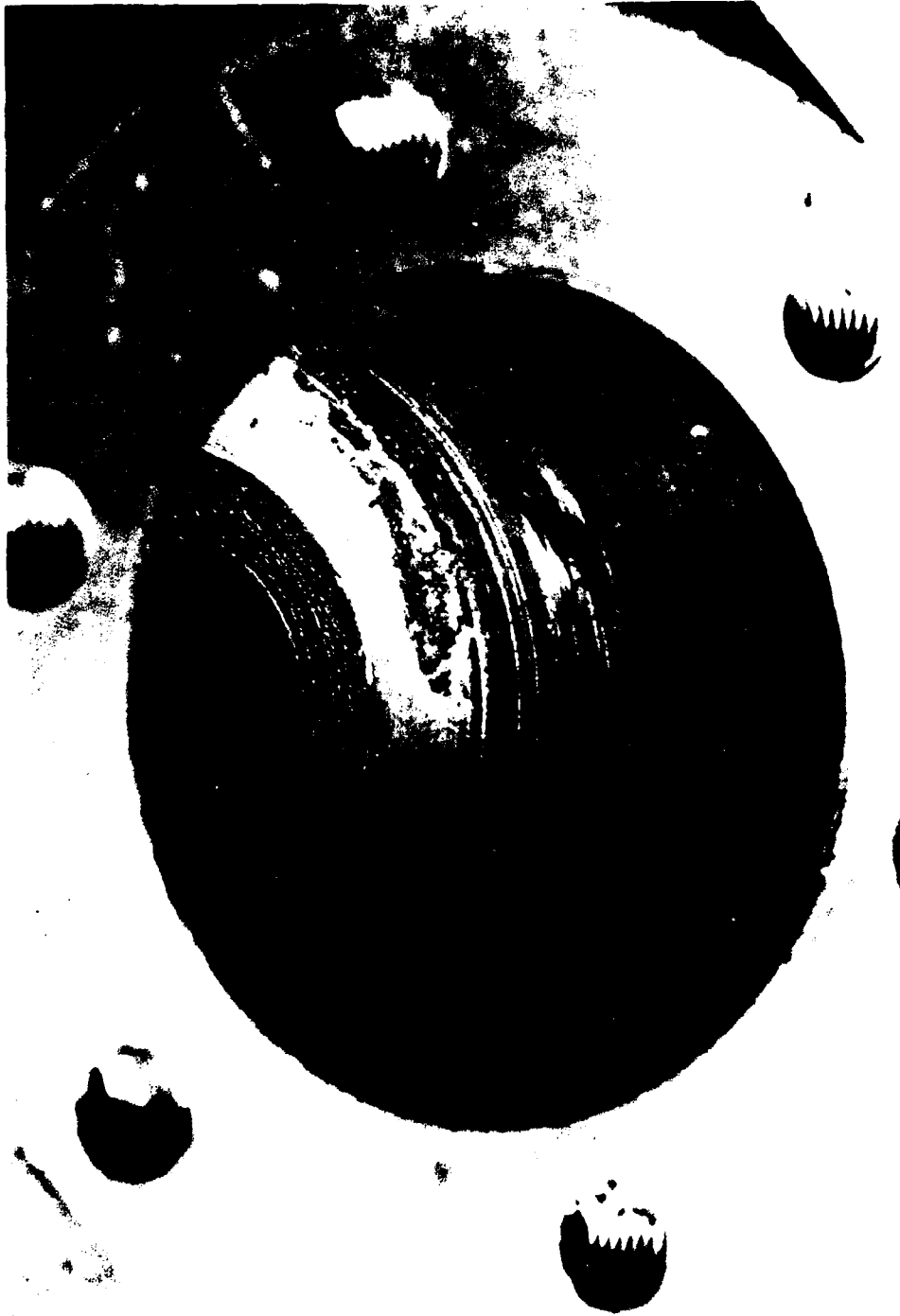


Figure 8. Wear on the Fuel-Oil Pump Body After 380-hr Operation



Figure 9. Worn Stator of Sewage Pump

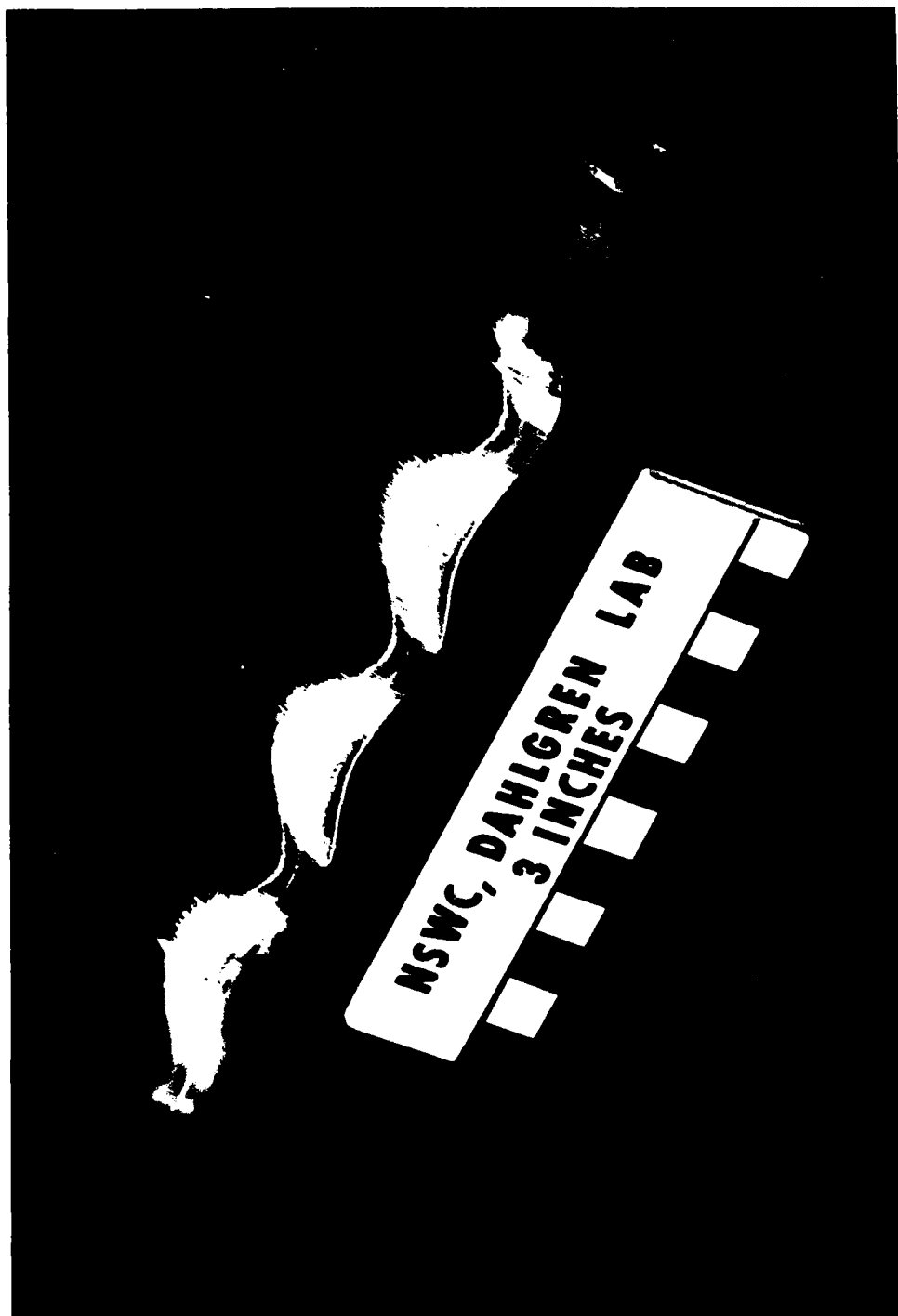


Figure 10. Worn Rotor of Sewage Pump

the stoking operation in progress. Test personnel wore protective garments during experimental testing to reduce the probability of injury from flying ashes and other debris should an aerosol can burst. Additionally, stoking was performed for 1 min no less than 30 min following the last hourly feed of solid waste so that solvent bottles and aerosol cans had time to "cook off," thus lessening, although not eliminating, the explosion hazard.

To reduce the problem of flying debris, the following concepts were evaluated: a deflector shield, a hopper screen, and a chain curtain. The shield and cover provided adequate protection; however, both interfered with operation of the stoking tool. The chain provided the best protection and allowed complete freedom of movement of the stoking tool. The chain curtain concept is being incorporated on the existing MFI-II, and future tests will confirm its effectiveness.

ASH REMOVAL

Routine cleaning included monthly removal of ash from the sewage chamber, weekly removal of fly ash from the multiple cyclone separator, and daily removal of residue in the ash bins. Buildup from freshwater sewage burns, Figure 14, was readily removed using a hoe; however, this required an individual to climb into the firebox, stand in the entrance of the sewage chamber, and rake ash from the sewage chamber walls and floor. Figure 15 shows the chamber after cleaning. Such actions are unacceptable since they require personnel to work in a confined, dusty environment, wearing protective clothing and dust masks. Provisions for cleanout from an external position are now being considered and will be incorporated in the existing incinerator.

Removal of the ashes and fly ash from the MFI-II system caused inconvenience to personnel because of resulting dusty conditions. Typical residue from the incinerator ash bins is shown in Figure 16. Although the manual provided some guidance, such as operating the fan during ash removal, a certain amount of dust still becomes dispersed in the incinerator area. Dust settling on electrical devices can produce premature failures, as cited previously. Additionally, there were several occurrences of smoldering material being present in the ash that could not be quenched until after weighing. The handling of the hot ashes required the operator to wear gloves and to use an insulated container to transport the ashes to a disposal area. Cleaning the fly ash collector was difficult because the surrounding area cannot be swept nor vacuumed effectively. Personnel dust masks worked only moderately well as protection against inhalation of the fine fly ash. The current approach to the solutions of the dust problems is to provide slide-on covers for the ash bins and an insulated enclosure to permit cooling prior to disposal.

CONSTRUCTION MATERIALS

Original space requirements were for an 8- X 8-ft X 7-ft-high space to house, operate, and maintain the MFI based on available space on board existing



Figure 11. Debris Behind Ram Face



Figure 12. Warpage of Ram Feeder Lining



Figure 13. Manual Stoking of YI-11 during Testing

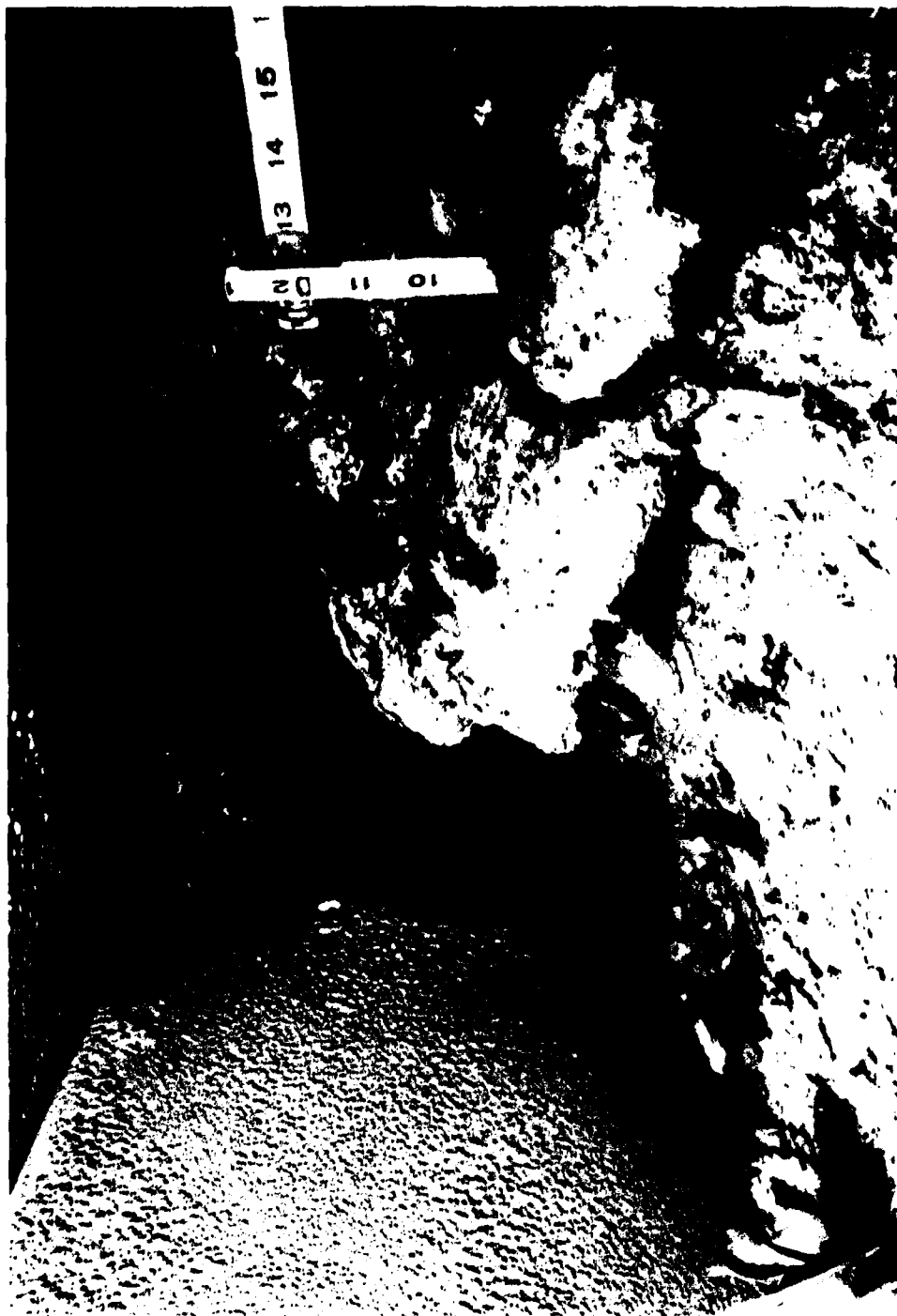


Figure 14. Ash Buildup During Freshwater Sewage Tests



Figure 15. Cleaned Sewage Chamber During Freshwater Sewage Tests

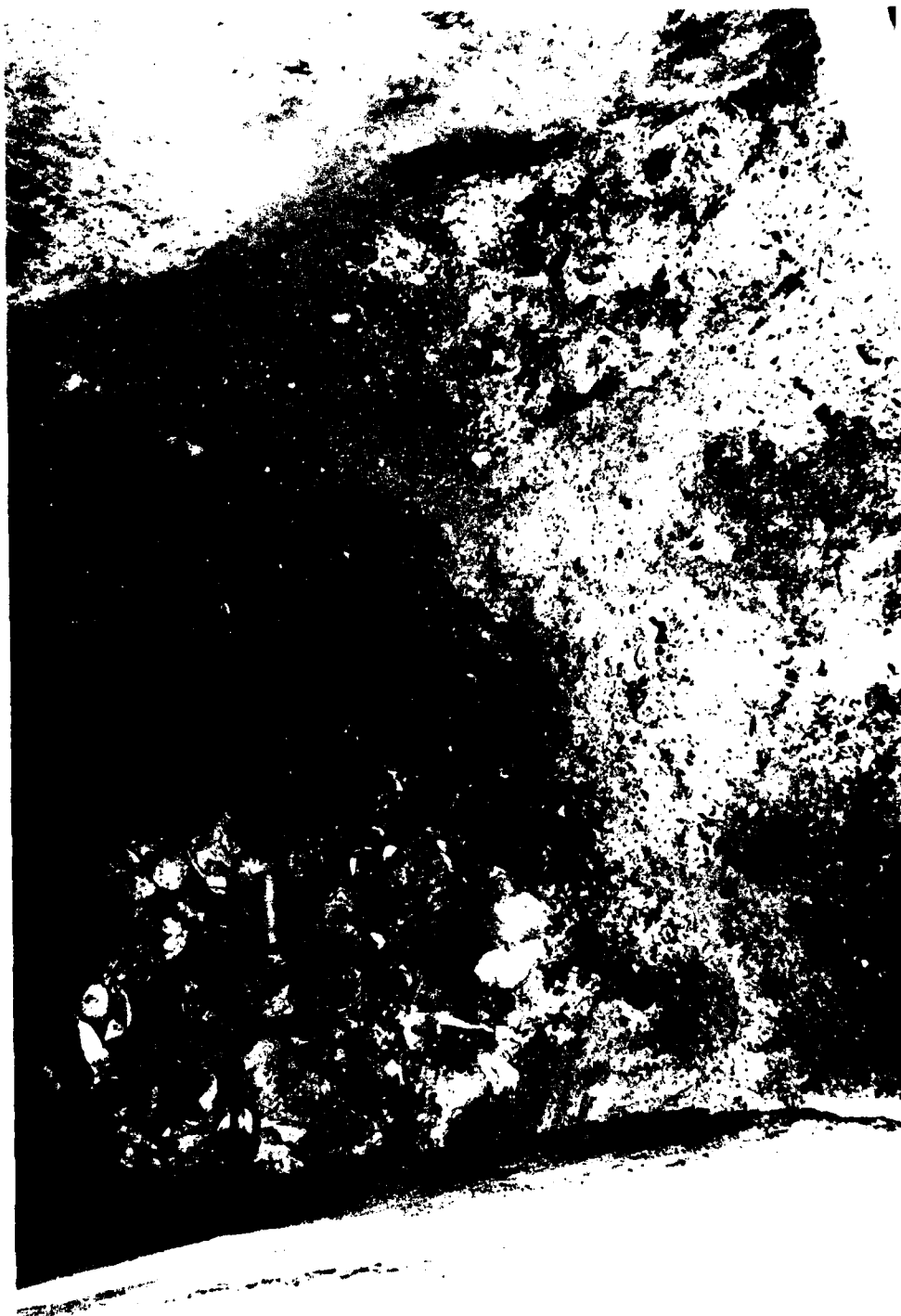


Figure 16. Incinerator Ash Residue

destroyers and frigates. A total system weight of 4000 lb was desired, based on the use of lightweight aerospace materials. Capacity requirements alone eliminated the space specification, and a revised value of 12 X 10 X 7-1/2 ft was chosen. Increasing the overall unit size and early failure of the lightweight material increased the weight to the present range of 11,000 to 12,000 lb. The majority of the incinerator liner material is a 97-percent tabular alumina castable with a service temperature of 3400°F. Areas that experience liquid impingement utilize a phosphate-bonded, alumina-chromic oxide plastic to withstand the severe environment.

The Phase II incinerator was initially fabricated, tested for capacity, and shipped from the contractor's facility near Boston, Massachusetts. The unit was transported on a commercial flatbed trailer approximately 480 mi to the test site in Dahlgren, Virginia. Careful inspection of the unit revealed fractured welds on the feed door frame and displacement of the refractory lining of the firebox. Frame corner welds exhibited cracks typical of those shown in Figure 17. The refractory displacement shown in Figure 18 occurred at regions where cracks developed during curing.

A redesign of the incinerator framework became necessary because of the vulnerability of the refractory to external vibrations and shock. The steel side panels were increased in thickness, and the refractory anchors were changed to sturdier S-shaped anchors (Figure 19) rather than the V-shaped anchors originally used to prevent movement of the refractory in any plane. Additionally, the anchors were bolted on all panels to facilitate future replacement of the refractory when necessary.

New wall panels were fabricated from mild steel plate. Careful edge preparation, longer bending radii, and stress-relieving procedures were employed to ensure defect-free components during cold-working phases of the fabrication. Magnetic particle inspection of high-stress areas was used as acceptance criterion for each panel. The area directly above the feed door opening was constructed with a recess to reduce the possibility of shell warpage due to heat dissipation from the refractory of the feed door. In addition, structural-channel, full-penetration continuous welds and improved refractory were used to reduce thermal stresses on the feed door opening. A detailed report of the fabrication and assembly has been published in an NSWC technical report.¹⁰ No defects were observed in the metalwork fabrication of the incinerator upon completion of 1257 hr of operation. Warpage, as discussed previously, was encountered with the ram feeder, which was original equipment for the Phase II unit.

The second major problem regarding construction material was the vulnerability of the refractory to burner flame impingement in the firebox and to saltwater sewage spray in the sewage chamber. As cited earlier, the two types of refractory primarily used were a 97-percent tabular alumina castable with a service temperature of 3400°F and a phosphate-bonded, alumina-chromic oxide plastic ram-applied refractory. The former is used for extreme temperature applications in furnace construction, and the latter is designed for severe metal and slag contact applications. During fabrication, the castable refractory is poured to conform with specified dimensions and allowed to set before

the plastic refractory is tamped in billets that interlock with the castable construction. The plastic refractory requires partial curing to prevent cold flowing prior to assembling of the incinerator module.

Upon curing, the castable refractory formed cure cracks on all vertical sections and more pronounced cracking on horizontal surfaces. By the end of the formal test program, the edges had worn round; however, no catastrophic failures of the castable material had occurred. Figures 20 and 21 show the sewage chamber roof before and after 1257 hr of testing. Two major areas of noticeable degradation were the burner flame impingement wall and the floor of the sewage chamber. Thin layers (1/8 in.) of refractory fused to firebox slag deposits, as shown in Figure 22, and were removed by brush cleaning during monthly maintenance. Small chunks, as shown in Figure 23, were also observed to be loose at cure-crack intersections after approximately 1000 hr of operation. As discussed earlier, fusion of ash cake to the refractory in the sewage chamber occurred during saltwater sewage processing. Figure 24 illustrates sewage ash accumulation on the "nose" area of the sewage chamber floor. Near completion of the test period, chunks were observed to fall from this area (Figure 25). Further inspection of the refractory revealed seepage of sewage to a depth of approximately 1 in. Figure 26 shows a cross section of refractory from this area. All areas exhibiting damage were determined to be repairable with a suitable patch material. No damage or deterioration was observed with the plastic refractory.

EMISSION CONTROL

The primary constraints on the emission control device were space, efficiency, and dry collection. A series of source emission tests (SETs) were performed to determine mass loadings in the exhaust gases during periods of burning garbage, trash, and refuse with fresh and saltwater sewage and without any sewage. Results showed grain loadings per standard cubic foot of dry flue gas (gr/ds ft³) corrected to 12-percent CO₂ in excess of the 0.2-gr/ds-ft³ design value for tests without sewage. With saltwater sewage, the design value of 0.5 gr/ds ft³ corrected to 12-percent CO₂ was also exceeded. Most recent tests in which freshwater sewage was burned with garbage, trash, and refuse produced average values of 0.44 gr/ds ft³ during trash burns, 0.39 gr/ds ft³ during refuse burns, and 0.42 gr/ds ft³ during burns with combinations of trash, garbage, and refuse.¹¹ It should be noted that these values are well above current Federal standard of 0.08 gr/ds ft³ corrected to 12-percent CO₂ for performance of any incinerator used to process solid waste by removing combustible matter. Additionally, the 2-percent sewage sludge (dry basis) processing requirement for the shipboard incinerator is not covered by Federal standards of performance for sewage treatment plants in which incineration is the ultimate means of disposal.¹² If the shipboard incinerator is required to meet specific emission standards, an alternate collector design may be necessary at the sacrifice of additional space.

Emission problems were also encountered when the primary burner fuel was changed from No. 2 fuel oil to JP-5 (a jet propulsion fuel). Stack gas opacity increased significantly, although burner adjustments were optimized for JP-5.



Figure 17. Corner Weld Failure of Feed Door Frame



Figure 18. Cracking of Original MFI-II Firebox Walls

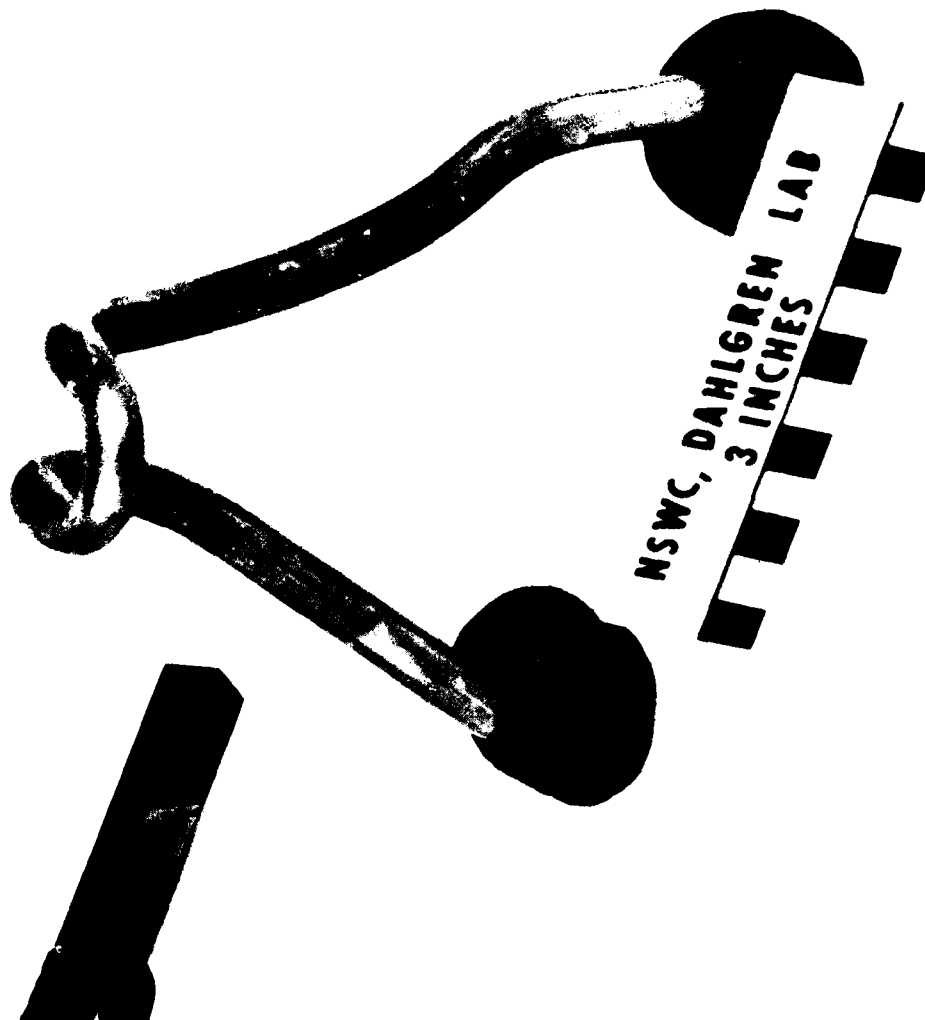


Figure 19. S-Shaped Refractory Anchors of MFI-II Unit



Figure 20. Sewage Chamber Roof Prior to Formal Tests



Figure 21. Sewage Chamber Roof After Formal Tests



Figure 22. Refractory Fused to Slag Deposit From Flame Impingement Wall

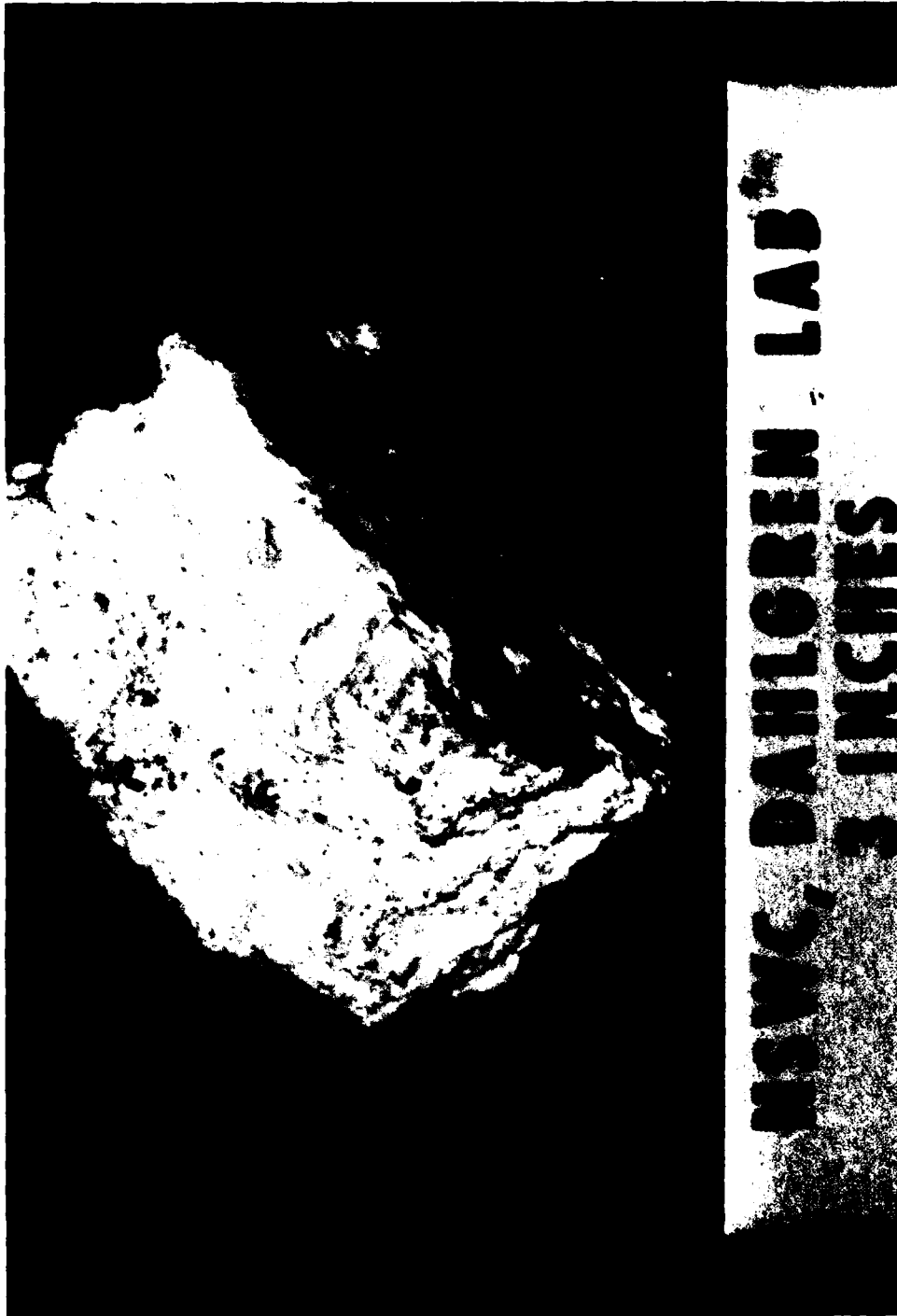


Figure 23. Refractory Chunk From Flame Impingement Wall

Trained-observer readings during freshwater SETs indicated opacity in excess of the 20-percent design requirement. Figure 27 represents the smoke plume for 1 min of stoking, and similar plumes were obtained when feeding high-plastic-content wastes. Figure 28 shows the stack under normal burning conditions with the fuel burner properly adjusted. Emission problems due to the burning of various fuels will be solved by efficient burner designs or specification of a particular burner setting for individual applications. A subjective evaluation was made by personnel from NAVSEC, NSWC, and a Naval Sea Systems Command (NAVSEA) consultant on stack gas odor during refuse and sewage burns. Figure 29 shows personnel at stack height during feeding operation. Consensus of the individuals involved was that no objectionable odors were discernible at any time during testing.

SAFETY

Exhaust Temperature

The MFI met the requirement for a flue exhaust temperature of less than 650°F. The maximum temperature recorded was 610°F without sewage and 570°F with sewage. The mean exhaust temperature was 485°F for the first 50 tests with no sewage and 461°F for the remaining 100 tests with sewage. Figure 30 illustrates temperature profiles during a typical test.

Surface Temperature

The required surface temperature for the exterior wall of the incinerator was below 140°F. This requirement was regularly exceeded during the first 50 tests, the highest recorded temperature being 246°F at the back wall adjacent to the plenum. When the room temperature exceeded 85°F, all four walls exceeded 140°F. A related problem was the rise in surface temperature after shutdown. Again, depending on ambient conditions, temperatures rose to approximately 230°F with the room temperature at 70°F before surface cooling began.

Tests were conducted to determine the effect of allowing the cooling jacket air fan to run under thermostatic control after system shutdown. The thermostat was located on the surface exhibiting the highest temperature throughout the testing. The cooling fan operated continuously for 6.9 hr after shutdown before the surface temperature was maintained below 140°F.

Other tests were conducted to determine the effect of a lower shutdown temperature setting on the firebox controller. As shown in Figure 31, reducing the surface temperature below the 140°F specification required a burndown period of 3.3 hr. If this extended burndown time is considered unacceptable, the increase of insulation thickness on the cooling jacket interior wall is the most likely alternative.



Figure 24. Sewage Runoff on Nose of Sewage Chamber Floor



Figure 25. Refractory Damage on Nose of Sewage Chamber Floor



NSWC, DAHLGREN LAB 3 INCHES

Figure 26. Cross Section of Refractory Chunk From Nose of Sewage Chamber Floor

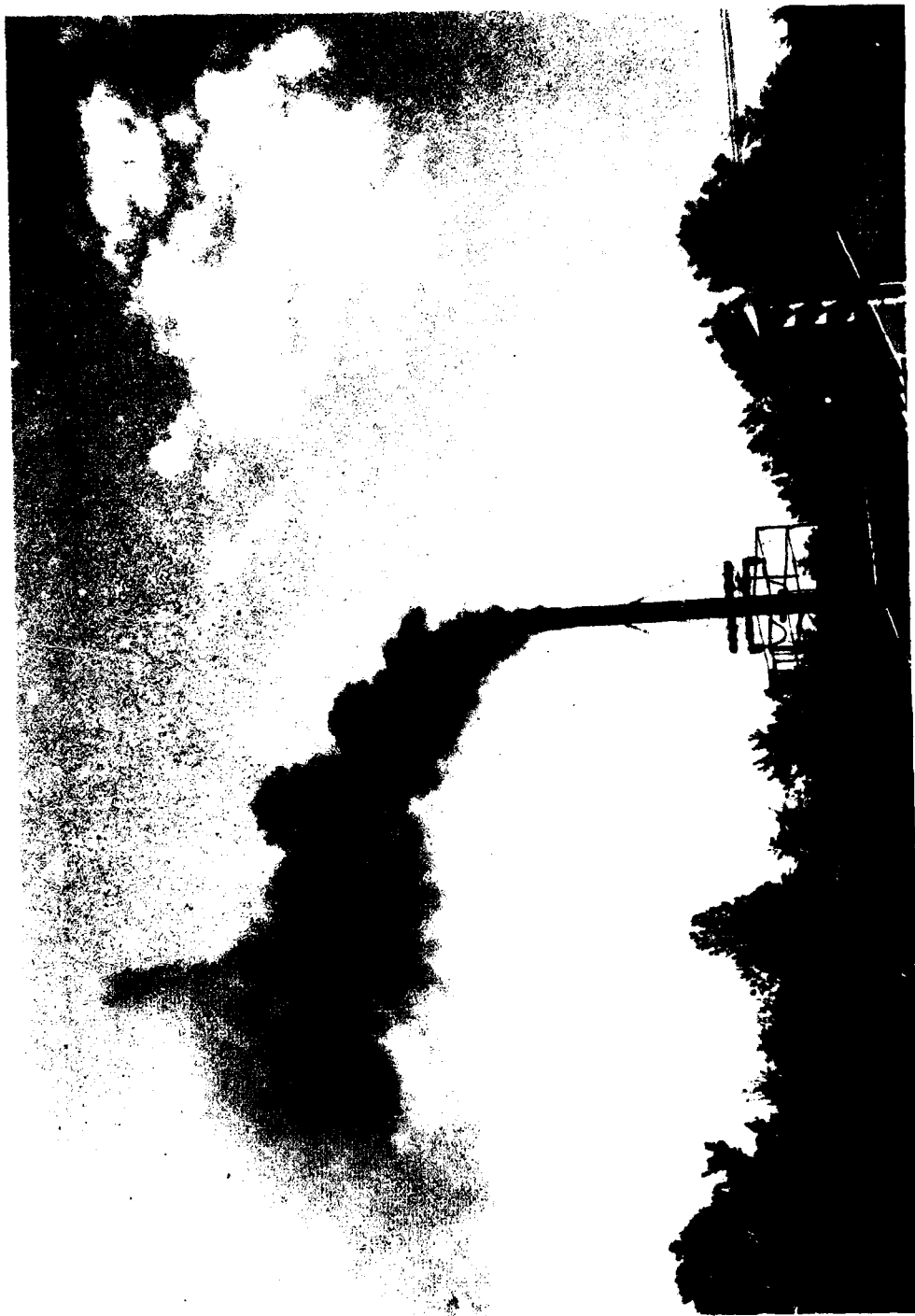


Figure 27. Stack Emissions During Stoking and Feeding of High-Plastic-Content Wastes



Figure 28. Stack Emissions During Normal Operating Conditions

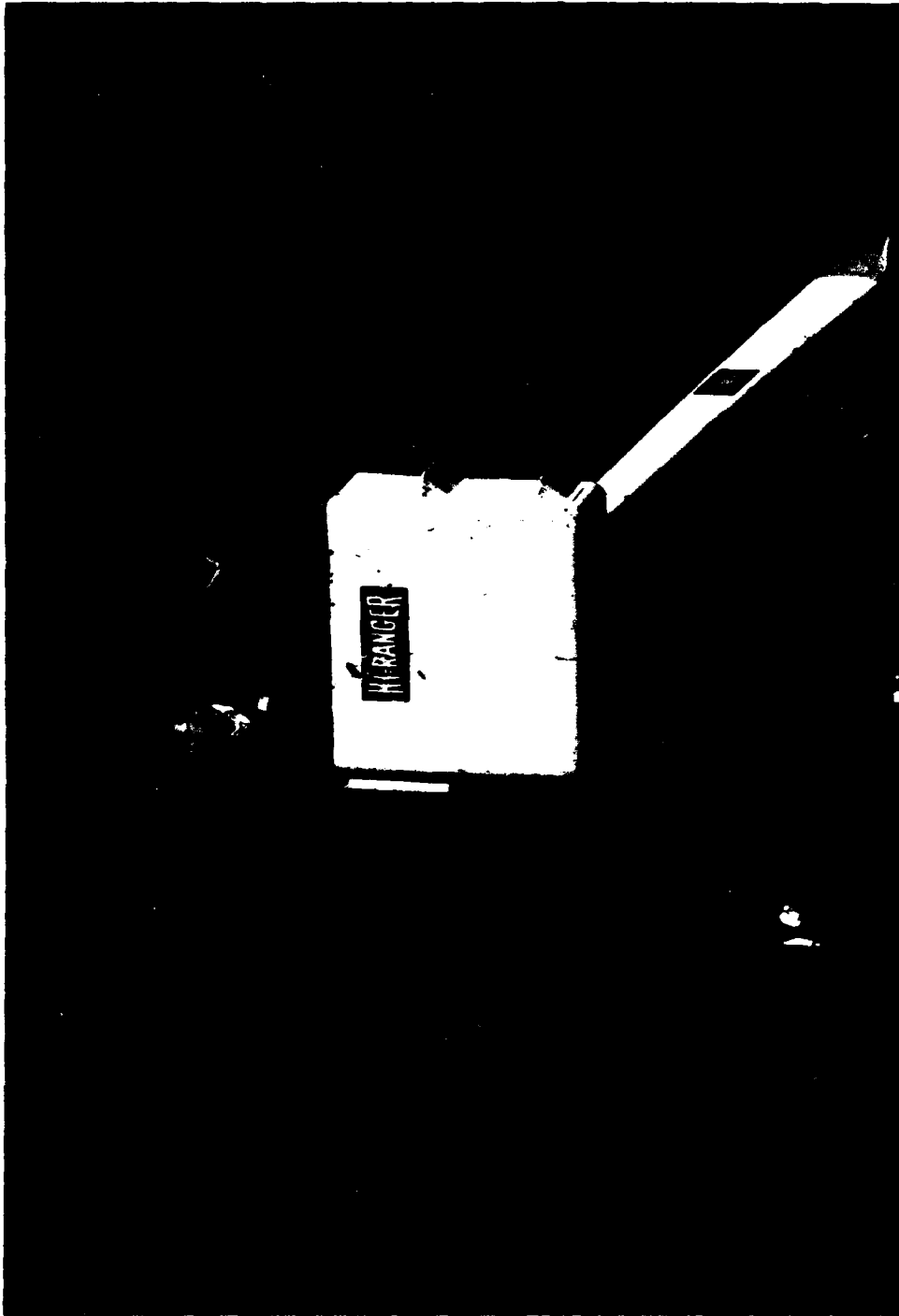


Figure 29. Odor Evaluation of MFI-II Stack Gases

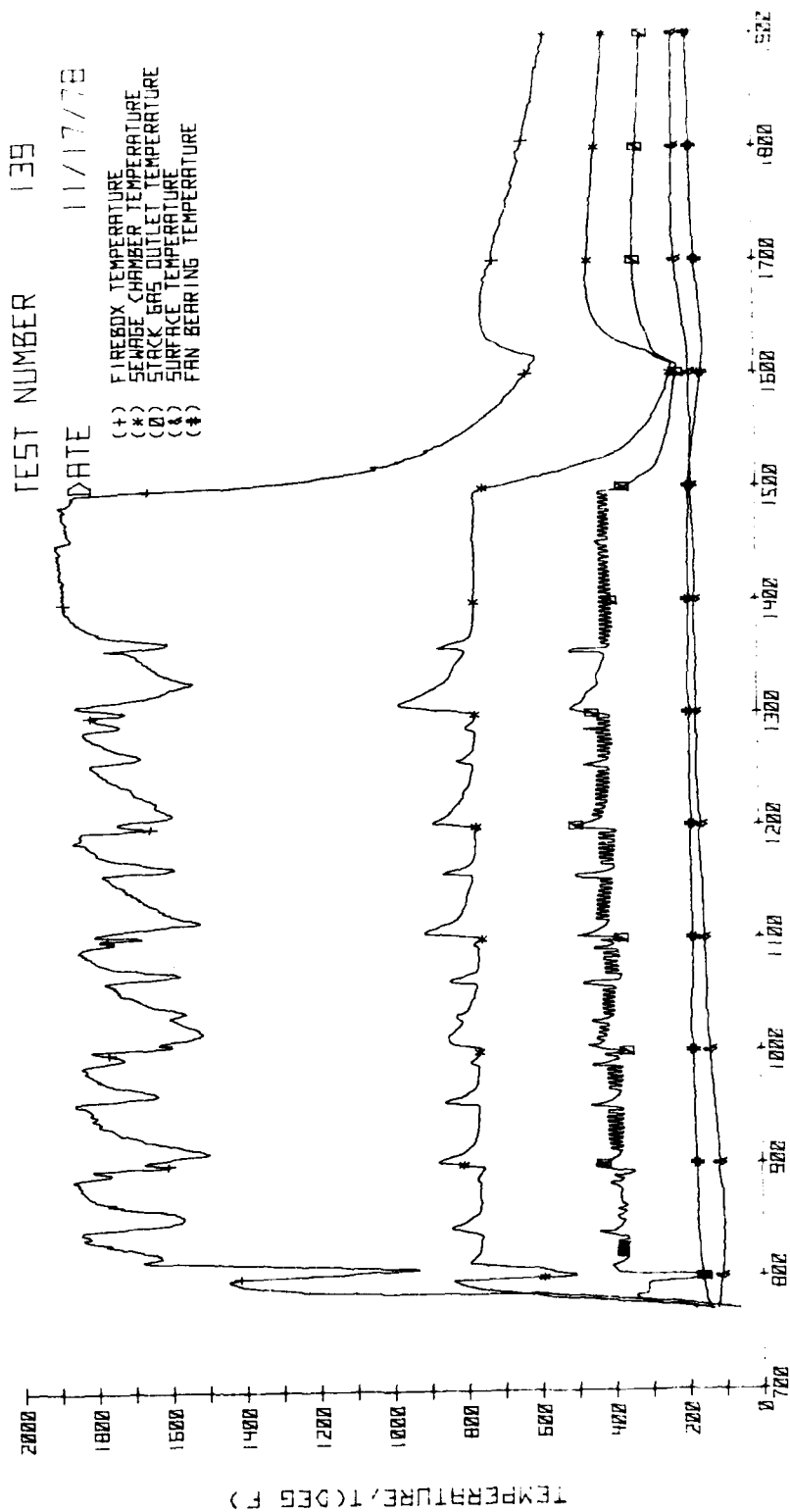


Figure 30. MFI Temperature Profiles

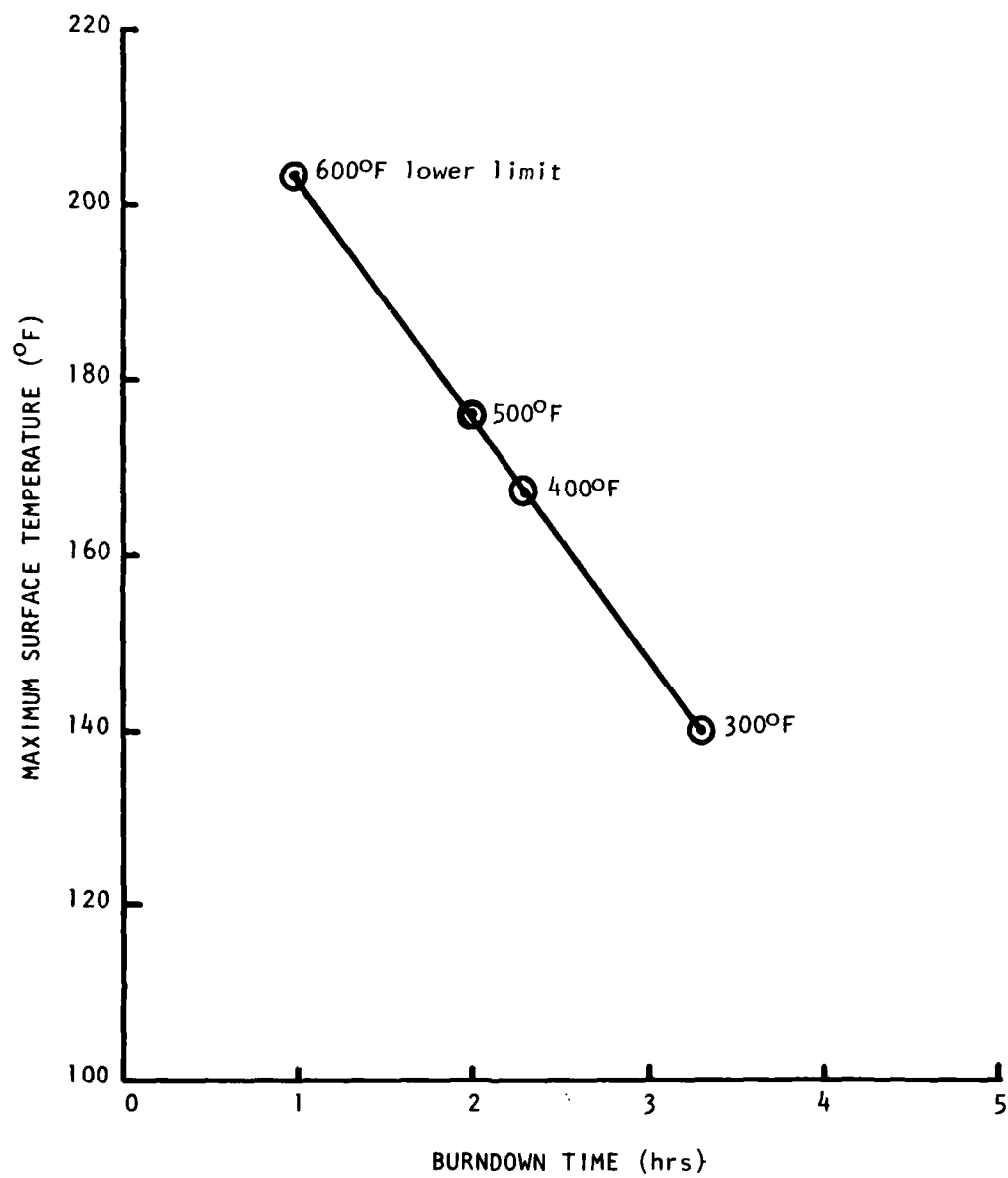


Figure 31. Surface Temperatures vs Burndown for Various Shutdown Limits

Operator Hazards

Certain safety problems other than those discussed under the stoking and ash removal sections had to be addressed to make the unit suitable for shipboard use. The pneumatic valve actuator was unguarded and acted as a pinch or blow hazard to unsuspecting personnel. Hot areas from penetrations (including the sewage chamber access port, sewage nozzle assembly and entrance, the back wall area adjacent to the plenum, and the wall area above the plenum) presented potential burn hazards. These regions always exceeded the surface temperature specifications, even though the room temperature was below 85°F. Expanded metal guards will be installed to eliminate this hazard.

Noise was not a problem as far as operator safety. The formal test plan required that the incinerator conform with Category D minus 10 dB of MIL-STD-740B (SHIPS) for noise criteria for shipboard equipment. Category D is the airborne grade level for machinery spaces. Noise evaluations were conducted twice during the formal test program, and test data showed that the MFI-II system met the necessary requirements during both tests.

Failsafes

During the first 600 hr of the evaluation, test personnel noticed that interlocks were needed for safe, efficient operation of the incinerator. Low air pressure or flameout of the main burner required automatic de-energization of the sewage pump. Power failures caused the feed door to close, sometimes catching the stoking fork under the door. Both items are correctable with minor wiring changes.

CONCLUSIONS AND RECOMMENDATIONS

A laboratory evaluation of the shipboard MFI for 1257 operational hr demonstrated that the solid waste processing requirements are acceptable for various wastes with a 98-percent average reduction efficiency on a weight basis. In addition to this requirement, freshwater sewage and waste oil can be adequately processed at the required flow rates. All wastes can be processed with an operator attention time of less than 5 min/hr.

Critical failure and corrective maintenance requirements were exceeded during the formal test program; however, the majority of the maintenance and failure items could have been prevented by an adequate maintenance section of the technical manual and proper specification of military standard materials. Projected estimates of MTBF and MTBCM were 1196 hr and 330 hr, respectively. The system met the maximum-time-to-repair criteria of 5 hr.

Requirements were met for flue gas temperatures of less than 650°F and noise criteria of Category D minus 10 dB of MIL-STD-740B (SHIPS). The extent of refractory deterioration was determined to be repairable with suitable patch material.

Certain safety hazards were identified through the evaluation period. Excessive surface temperatures, moving mechanical components, and problems with exploding aerosol cans during stoking, as well as high dust levels during ash removal, were observed. Proper installation of expanded metal guards and insulation will eliminate excessive temperatures. Adequate guards and covers will prevent exposure of operating personnel to flying debris and fine dust.

Recommendations for deficiencies include provisions for insulation and thermostatic control to reduce surface temperatures; development of adequate preventative maintenance instructions for the oil burner and ram feeder; updating of the technical manual with better maintenance criteria and manufacturers' instructions to reduce maintenance times, based on the results of the laboratory evaluation; and optimization of the automatic feed system controls, fail-safes, and fuel-burner system.

After completing the modifications discussed and instituting the recommendations above, an evaluation for shipboard vibration will complete evaluation of all requirements. If the shipboard vibration criterion is met, the MFI will be suitable for installation on board a naval vessel for shipboard evaluations and approval for service use.

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APPENDIX
FAILURE REPORTS

BURNER MOTOR

The motor of the Industrial Combustion Model AM3CM oil burner failed to operate properly during Test 116 on 10 October 1978. The elapsed time indicator reading was 1362.8 hr at the time of failure. The failure occurred when the incinerator was started for the daily test. The burner motor starter relay showed an overload and was reset, resulting in the burner motor's starting and running. The burner ignited and burned poorly, and the firebox reached a maximum temperature of 900°F. No manipulation of oil pressure, atomizing air pressure, or secondary air draft changed the poor performance of the burner. The voltage and amperage of the burner motor were checked to determine if the electrical requirements of the motor were correct. The voltage for the motor was 400 V, and the amperage exceeded the value of 1.35 A on the motor specification plate by 0.5 A per phase. This indicated an unusual load condition for the motor. The incinerator was placed in burndown mode and allowed to shut down. The Dayton Model 2N924G 3 phase A.C. motor was replaced by an identical motor from the Phase I oil burner. The motor required 25 min (0.4 man-hour) to troubleshoot and 20 min (0.3 man-hour) to remove and replace. Total downtime was 1 hr 5 min. The replacement motor operated within the given electrical specifications, and the burner performance was improved. Startup and operation of the incinerator proceeded in a normal fashion.

The cause of the motor failure was determined to be the breakdown of bearing lubrication.

FIREBOX TEMPERATURE CONTROLLER

The Fenwall Model 524 temperature controller was replaced after it failed to give proper temperature readings. The temperature meter indicated a temperature below zero. The failure occurred during Test 118 on 12 October 1978. The failure was noticed at 1020 hr, which was approximately 3 hr after startup. The elapsed time indicator reading was 1382.0 hr. The problem was isolated at the temperature controller after checking the firebox thermocouple and its leads for a shorted circuit. The failure occurred during the burning of refuse and freshwater sewage. The sewage temperature controller was maintaining the burner operation, and the operation of the incinerator was not affected by the firebox temperature controller's having a negative temperature reading. Two procedures were tried to determine the effects on the incinerator's operation. The sewage burn operation was stopped, which returned the temperature control to the Fenwall 524 temperature controller. The burner came on and remained in operation and would have overheated the incinerator had it not been removed from control by returning to the sewage burn mode. Burndown was initiated before the unit was replaced, and the incinerator was immediately shut down. The conclusion of these tests is that the operation of the incinerator was not affected during sewage burn operation, but startup and burndown operations are adversely affected. Startup set point would not be reached, which prevents

sewage or waste oil burn operations. If in-operation and sewage burn mode is interrupted, overheating of the incinerator can occur. If failure occurs during operation, the burndown mode would not function, shutting the incinerator down instantly and possibly overheating the fans and affecting the refractory.

METERING FUEL PUMP

The metering fuel pump on the oil burner of the MFI was replaced because of poor burner performance. The elapsed-time indicator (ETI) reading was 1529.9. The pump problem was evidenced by smokey flames, poor ignition, and irregular oil flows. This occurred after Test 134 on 7 November 1978. The removal/replacement required 2 hr (4 man-hour) to complete and an additional 2 hr to tune the burner for smokeless operation.

The pump is a combination air compressor/oil pump used for providing air for atomization and control functions and oil flow to the nozzle. The oil section of the pump showed some abrasion, but the majority of the problems were caused by rust and sludge buildup in the pump. The air compressor section was in excellent shape.

The replacement procedure for this pump should be included in the technical manual. The tuning of the burner may not be required, but its operation must be checked by a qualified burner technician. The need for a better fuel delivery system, which prevents sludge from entering the pump, will reduce this type of failure; but the rusting is probably caused by the saltwater present in the waste oil. Periodic cleaning may be required to remove the rust formation, or the pump material may be changed to a rust-resistant material.

FEED DOOR PNEUMATIC CYLINDER

The failure occurred on 6 December 1978 during Test 150. The ETI reading was 1686.1. The symptom of the failure was lack of lifting power by the door cylinder. The diagnostic test showed that the piston seals were leaking. This test consists of removing the upper air connection and determining if air is leaking past the seals. If the seals are good, no air should come past the seals. If the seals are bad, airflow will be present. In this particular case, the seals leaked badly. This is not the only possible mode of failure in this system because the rod seals and cushion seals could also fail, causing leakage of air to the outside of the cylinder. This leakage would be noticeable unlike the piston seal failure, which is an internal leakage.

The cylinder had to be removed from the incinerator, which required three men 1-1/2 hr to repair. Instructions for assembly and disassembly were not

readily available. The removal of the cylinder requires large wrenches to loosen the double universal joints at both ends of the cylinder. These joints are difficult to remove easily because of the lack of area around the joints.

The disassembly of the cylinder is uncomplicated and is accomplished by using a ratchet drive and socket with a box wrench to remove the four tie rods. Once this is accomplished, the piston rod can be separated from the cylinder. The piston is on a threaded end of the piston rod and held by a set screw. The set screw was found to be damaged by previous abuse and had to be removed with a screw extractor. The repairman should take care in tightening the set screw to prevent damage to the set screw and the threads of the rod. The removal and replacement of the piston seals were simple tasks; and, once these tasks were completed, the piston rod was placed in the cylinder, and the tie rods were replaced and tightened. The cylinder was then installed on the door of the incinerator. The removal and installation of the cylinder required 1 hr total for both operations. The replacement of the seals required 30 min but would have taken half the time if the set screw had not been damaged.

It is recommended that repair and assembly/disassembly instructions be included in the technical manual. Also, the Neoprene seals and gaskets should be replaced with fluoroelastomer seals and gaskets on all of the pneumatic cylinders of the MFI.

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